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Sustainable manufacturing of consumer appliances: Reducing life cycle environmental impacts and costs of domestic ovens

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ABSTRACT

Electric ovens are among the least energy efficient appliances, with the efficiency of only 10%–12%. With new policy instruments in Europe requiring energy reduction, manufactures are seeking to develop more efficient domestic appliances. The aim of this paper is to aid sustainable manufacturing of an innovative, highly-efficient oven (HEO) by evaluating its life cycle environmental impacts and costs in comparison to conventional ovens. The results suggest that the HEO has 9%–62% lower environmental impacts than conventional ovens with the equivalent savings in the life cycle costs ranging from 25% to 61%. Replacement of conventional ovens by HEO in Europe (EU28) would save 0.5–5.2 Mt of CO_2 eq. and the life cycle costs would be lower by €0.5–1.96 billion (10^9) per year. At the household level, energy consumption would be reduced by up to 30% and consumer costs by 25%–50%. These results suggest that policy measures should be put in place to encourage the uptake of energy efficient ovens by consumers.

Keywords: Life cycle assessment; Life cycle costs; Domestic ovens; Sustainable manufacturing

1. Introduction

It is estimated that there were 185.3 million cooking appliance units globally in 2015 (Global Industry Analyst, 2011) with the market value expected to reach $231 bn by 2018 (Data Monitor Research, 2014). In Europe, around 12 million electric ovens are sold each year (Eurostat, 2009). Electric ovens are among the least energy efficient appliances, with the efficiency of only 10%–12%. Given that they consume 100–300 kWh per year (Fonseca et al., 2009) and that 61% of 213.8 million households in the European Union (EU28) have electric ovens (Bertoldi et al., 2001), this amounts to around 26 TWh of electricity per year. If their efficiency increased by only 20%, that would mean a saving of around 5 TWh of electricity annually. In an attempt to stimulate reduction of energy use by domestic appliances and particularly ovens, the EU has adopted several policy instruments, including the Energy Labelling Directive (EC, 2013a). The Directive, which for ovens came into force in January 2015, classifies ovens into seven categories, from A+++ to D, based on the energy efficiency of the oven cavity. The Directive requires manufacturers and retailers to display on a label the energy consumption by the oven (expressed in kWh per cycle) based on a standard load.

In anticipation of the Directive, manufactures have been seeking to develop more efficient appliances. This paper considers sustainable manufacturing of a new highly-efficient oven (HEO), being developed by Whirlpool, one of the largest oven manufacturers in the world. The primary aim of developing the HEO is to increase the energy efficiency of domestic ovens during use by around 30% relative to

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conventional ovens. A further aim is to improve energy efficiency of oven manufacturing. These improvements are also expected to reduce the costs to consumers and the manufacturer as well as to lead to substantial savings in environmental impacts. To quantify these potential benefits, HEO is compared here to conventional ovens using life cycle assessment (LCA) and life cycle costing (LCC). To our knowledge, this is the first study of its kind for domestic ovens. The following section details the methodology, followed by the discussion of the results in Section 3 and conclusions in Section 4.

2. Methodology

The LCA methodology follows the guidelines in ISO 14040/44 (ISO, 2006a,b) and 14044 (ISO, 2013). The environmental impacts have been estimated as follows (Azapagic et al., 2007):

$$B_j = \sum_{i=1}^{I} b_{j,i} x_i \quad j = 1, 2, \ldots, J \tag{1}$$

$$E_k = \sum_{j=1}^{J} ec_{k,j} B_j \quad k = 1, 2, \ldots, K \tag{2}$$

where:

$b_{j,i}$ environmental burden j per unit activity i, with burdens representing raw materials and energy used in the system and emissions to air, water and land

x_i mass or energy flow associated with unit activity i

$e_{k,j}$ relative contribution of the total burden B_j to impact E_k as defined by the CML 2001 method (Guinée et al., 2001).

The focus of the study is on the global warming potential (GWP) but the following impacts are also considered to ensure that greenhouse gas emissions are not reduced at the expense of other aspects: acidification, eutrophication, ozone layer depletion, photochemical smog and human toxicity. The eco-toxicity categories are not considered due to a lack of data and the associated uncertainty.

The LCC methodology is congruent with LCA and follows the approach developed by UNEP and SETAC (UNEP and SETAC, 2009) and Swarr et al. (2011) The life cycle costs have been estimated according to:

$$LCC = C_{RM} + C_M + C_U + C_W \tag{3}$$

where:

LCC total life cycle costs over the lifetime of the oven

C_{RM} costs of raw materials

C_M costs of manufacturing

C_U costs of use of ovens over the lifetime, including electricity and cleaning agents

C_W costs of end-of-life waste disposal.

The CCaLC v3.1 software (CCaLC, 2013) has been used to model the system and estimate both the environmental impacts and life cycle costs. The following sections detail the goal of the study, system boundaries, data and assumptions.

2.1. *Goal and scope of the study*

The main goal of the study is to assess the life cycle environmental impacts and life cycle costs of the HEO and quantify the environmental and economic benefits relative to conventional ovens. As described further below, the only difference in the design of the two oven types is the cavity, so that the study considers only this part of the oven. As illustrated in Fig. 1, the system boundary includes production of the raw materials used to manufacture the cavity, the manufacturing process, use of the oven and end-of-life waste management. Transport is excluded as it contributes less than 0.1% to the impacts and costs.

Both ovens have the same volume of the cavity (73 litres) but they are made from different materials: low-carbon steel and enamel are used for the conventional oven, while the HEO cavity is made using stainless steel and sol–gel (Fig. 2). Stainless steel is used for the HEO because of its high reflectivity (Fig. 3) and ease of cleaning, while the sol–gel coating prevents loss of reflectivity owing to metal oxidation which occurs at high temperatures, a common problem in conventional enamel-based oven cavities. The manufacturing process for both ovens is the same except for the enamelling process for the conventional oven and application of sol–gel for the HEO. Therefore, only the enamelling and application of sol–gel are considered, respectively, in the manufacturing stage.

The substrate material for the enamel layer in the conventional oven is a low-carbon enamelling grade steel formed into a cavity. The stainless steel substrate for the HEO cavity is produced at supplier in the form of coil. A protective film is then applied to the coil, which is then rolled and shipped to the in-house post-coating line. The coil is unwound and cut into appropriate panel dimensions after which the protective film is removed and the panels degreased. The first sol–gel coating is applied in a liquid-spray coating stage, dried, cured and allowed to cool down. Subsequently, the second sol–gel layer is applied again in another liquid-spray coating stage, dried, cured and allowed to cool down. The coated panels are then sent to the manufacturing line after application of a protective film.

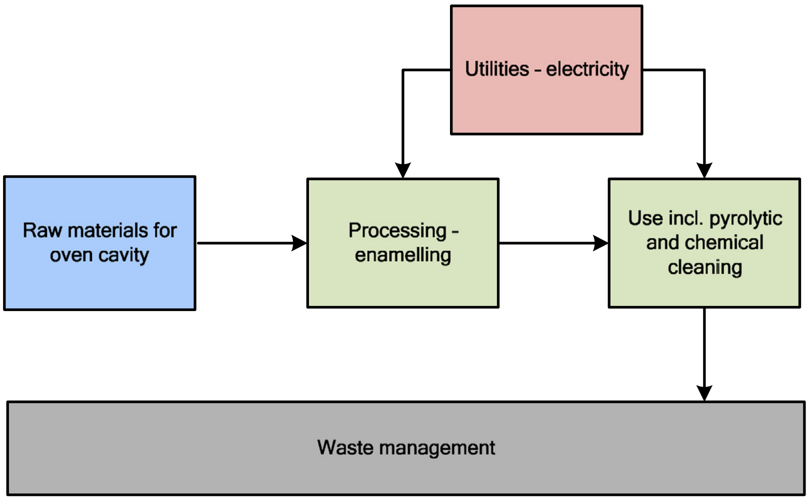
The use stage includes electricity consumed and oven cleaning over its lifetime. The conventional oven can be cleaned either by using chemicals (aerosol oven cleaners or traditional dish-washing detergents) or a built-in pyrolytic self-cleaning cycle in which the oven is heated to over 400 °C to reduce any deposits to a thin layer of ash, which can then be cleaned away easily. The HEO, on the other hand, can be cleaned using traditional dish-washing detergents.

The unit of analysis (functional unit) of the study is defined as the 'manufacture of 1 domestic electric oven cavity and its use over a lifetime of 19 years'. This lifetime is based on the average lifetime of ovens estimated by Mudgal et al. (2011); however, a shorter lifetime is considered as part of a sensitivity analysis. The oven is manufactured in Italy and assumed to be used in the EU28 region.

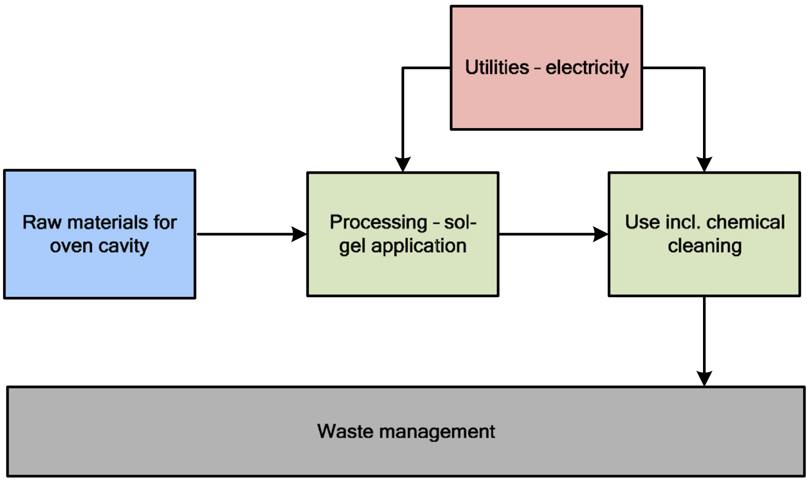
2.2. *Data and assumptions*

Tables 1–3 summarise the data used in the study and their sources. As indicated in the tables, primary production data have been sourced from Whirlpool Europe while the secondary data have been obtained from LCA databases and the literature.

For the use stage, 110 use cycles are assumed annually over 19 years for both types of oven. The conventional oven consumes 0.69 kWh of electricity per cycle as measured by the manufacturer in accordance with the standards CSA



(a) Conventional oven.



(b) Highly-efficient oven.

Fig. 1 – Scope of the study and system boundaries for the two types of the oven.

(a) Conventional oven.

(b) Highly-efficient oven.

Fig. 2 – The cavity of the conventional and HEO ovens.

C358-03 (R2008) (CSA, 2008), IEC 60350-1:2011 (IEC, 2011) and EN 50304 and 60350 (BSI, 2009). For the pyrolytic cleaning of the conventional oven, 10 cleaning cycles have been assumed annually, based on a consumer survey carried out by Whirlpool. The short cleaning cycle consumes 3.5 kWh of electricity and lasts for 75 min, while the long cycle takes 120 min and uses 6.5 kWh; both are carried out at 440 °C.

For the HEO, three options are considered for electricity usage per cycle, including oven pre-heating (155 °C over 13 min as stipulated by IEC 60350-1:2011 IEC, 2011): 0.63 kWh (HEO1), 0.59 kWh (HEO2) and 0.49 kWh/cycle (HEO3), all measured on the pilot line, also in accordance with the above-mentioned standards. These options have evolved over the course of the oven development process and each has been assessed for

Table 1 – Raw materials for the conventional and highly-efficient ovens.

Raw materials	Amount (kg/oven)	Cost (€/oven)	Sources of amount and cost data	Sources of LCA data
Conventional oven				
Low carbon steel	7.97	5.97	Manufacturer	ELCD and ESA (2011)
Enamel	0.62	1.20	Manufacturer	Ecoinvent (2010)
Cleaning agent (aerosol oven cleaner)	3.80	57.63	Manufacturer	Ecoinvent (2010)
Cleaning agent packaging				
Aluminium can	0.84	–[b]	Own measurement[c]	CCaLC (2013)
HDPE (top)	0.13	–[b]	Own measurement[c]	Ecoinvent (2010)
LDPE (label)	0.024	–[b]	Own measurement[c]	Ecoinvent (2010)
Highly-efficient oven				
Stainless steel (HEO1& HEO2)	6.33	10.76	Manufacturer	ELCD and ESA (2011)
Stainless steel (HEO3)	5.08	9.65	Manufacturer	ELCD and ESA (2011)
Sol–gel/IPA coating layer A + B	–[a]	1.29	Manufacturer	Ecoinvent (2010)
Cleaning agent (detergent)	0.95	2.67	Manufacturer	Ecoinvent (2010)
Cleaning agent packaging				
PET (bottle)	0.89	–[b]	Own measurement[c]	Ecoinvent (2010)
HDPE (top)	0.13	–[b]	Own measurement[c]	Ecoinvent (2010)

[a] Confidential data.
[b] Included in the cost of the cleaning agent.
[c] For the amount of packaging.

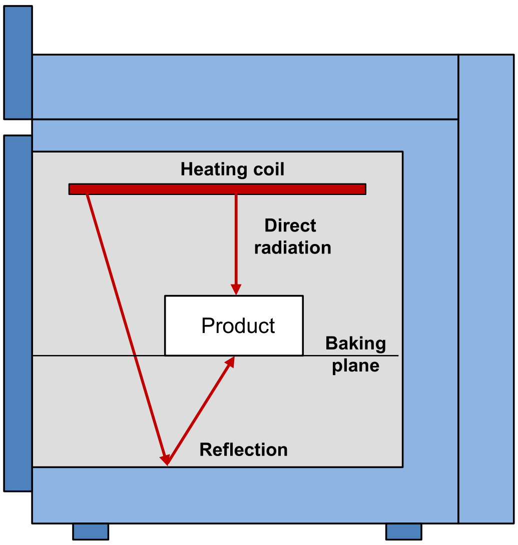


Fig. 3 – A graphical depiction of the working principle for the highly-efficient oven.

the environmental and economic sustainability relative to the conventional oven to help improve energy efficiency of the next design. This has led not only to a 30% increase in the efficiency in the use stage relative to the conventional oven, but also a two times higher efficiency of oven manufacturing (Table 2); the latter is due to the lower temperature required for curing the sol–gel coating compared to the conventional enamelling process.

The price of electricity for industrial use in Italy is estimated at €0.167 per kWh (EC, 2013b), including market price, transmission through networks, administrative charges, non-recoverable taxes and duties. The average domestic electricity prices in the EU28 have been estimated at €0.176 per kWh (EC, 2013b). In the base case, it is assumed that domestic electricity prices remain constant over time; however, the effect of increasing energy prices over time is explored within the sensitivity analysis.

For end-of-life waste management, it is assumed that 80% of oven steel is recycled (ELCD and ESA, 2011) and 20% landfilled, while all the enamel is assumed to be landfilled

Table 2 – Electricity consumption for the conventional and highly-efficient ovens[a].

Process stage for energy use	Amount (kWh/oven)	Cost (€/oven)
Conventional oven		
Enamelling	5.0	0.8
Domestic use	1442.1[b]	253.8
Pyrolytic cleaning (short cycle)	665.0[c]	117.0
Pyrolytic cleaning (long cycle)	1235.0[c]	217.4
Highly-efficient oven		
Sol–gel coating	2.4	0.4
Domestic use (HEO1)	1316.7[d]	231.7
Domestic use (HEO2)	1233.1[d]	217.0
Domestic use (HEO3)	1024.1[d]	180.2

[a] Source of electricity consumption data: oven manufacturer. Source of LCA data for electricity for EU28: Ecoinvent (2010). Source of cost data for EU28: EC Energy Portal (EC, 2013b).
[b] Assuming 110 cycles annually over the lifetime of 19 years and electricity consumption of 0.69 kWh per cycle.
[c] Assuming 10 cycles annually over the lifetime of 19 years and electricity consumption of 3.5 and 6.5 kWh per cycle for the short and long cycle, respectively.
[d] Assuming 110 cycles annually over the lifetime of 19 years. Electricity consumption: HEO1: 0.63 kWh per cycle; HEO2: 0.59 kWh per cycle; HEO3: 0.49 kWh per cycle.

(Table 3). The system has been credited for the recycled materials.

2.3. *Data quality and uncertainty*

To assess the uncertainty in the data and results, a data quality assessment has been carried out following the CCaLC methodology (CCaLC, 2014) which is described in Supplementary Information S1 (see Appendix A). Based on the five criteria considered (data age, geographical origin, source, completeness and reproducibility, reliability and consistency), the quality of both the LCA and LCC data is estimated to be high. Therefore, the results can be considered to have high certainty. For full details on the data quality assessment, see Supplementary Information (see Appendix A).

Table 3 – End-of-life data for the conventional and highly-efficient ovens.

Waste	Amount[a] (kg/oven)	Cost (€/oven)	Type of disposal	Sources of LCA data	Sources of cost data
Conventional oven					
Steel	7.97	0.11	80% recycled[b] 20% landfilled	CCaLC (2013)	Hogg (2012)
Enamel	0.63	0.04	Landfilled	Ecoinvent (2010)	Hogg (2012)
Aluminium (can)	0.84	0.06	48% recycled[b] 52% landfilled	CCaLC (2013)	Hogg (2012)
HDPE (cap)	0.13	0.01	Landfilled	Ecoinvent (2010)	Hogg (2012)
LDPE (label)	0.02	0.002	Landfilled	Ecoinvent (2010)	Hogg (2012)
Highly-efficient oven					
Stainless steel (HEO1 & HEO2)	1.27	0.09	80% recycled[b] 20% landfilled	CCaLC (2013)	Hogg (2012)
Stainless steel (HEO3)	1.02	0.07	80% recycled[b] 20% landfilled	CCaLC (2013)	Hogg (2012)
PET and HDPE	1.02	0.07	Landfilled	Ecoinvent (2010)	Hogg (2012)
Cleaning agent (detergent)	0.95	0.001[c]	Wastewater treatment	Ecoinvent (2010)	Media Analytics (2011)

[a]Source of data as in Table 1.
[b]The system has been credited for recycling.
[c]Corrected for inflation to 2013 prices.

3. Results and discussion

The next sections first present the results for the environmental impacts, followed by a discussion of the life cycle costs. The influence on the results of different parameters and assumptions is explored subsequently in the sensitivity analysis in Section 3.3. Finally, the potential implications for the environmental impacts and life cycle costs at the EU28 level are considered in Section 3.4.

3.1. *Environmental impacts*

As can be observed in Fig. 4, the total GWP for the conventional oven ranges from 812–1478 kg CO_2 eq. over the lifetime of 19 years, depending on the cleaning method assumed, with the long pyrolytic cleaning having the highest impact and the use of oven cleaner the lowest. For the HEO, the lifetime impact ranges from 738 kg CO_2 eq. for HEO1 to 576 kg CO_2 eq. per oven for HEO3. Therefore, the GWP of HEO relative to the conventional oven is reduced from 9%–61%, depending on the assumptions.

As also shown in Fig. 4, the main contributor to the impact for the conventional oven is the use stage, owing to the energy used over the lifetime of the oven. The contribution of end-of-life waste management, which is included within the use stage in Fig. 4, is negligible (∼1%). Pyrolytic cleaning is the second most important contributor to the GWP, also because of the energy consumption (see Table 2). The contribution of the raw materials is also negligible (∼1%). For the HEO, the energy use accounts for the large majority of the impact (97%). Stainless steel adds a further 2%, sol–gel around 1% and manufacturing of the oven cavity 0.2%. As for the conventional oven, the end-of-life waste management contributes less than 1% to the impacts across all the HEO options considered.

The other life cycle impacts are also lower for the HEO than for the conventional oven (Fig. 5). For example, relative to the conventional oven with the long pyrolytic cycle, the environmental savings for HEO1 range from 48% (photochemical smog) to 51% (eutrophication, ozone layer depletion and human toxicity) and for HEO3, from 58% to 62%. If the use of oven cleaner is assumed for the conventional oven instead of pyrolytic cleaning, then the savings for the best option, HEO3, are between 24% and 42%. Like the GWP, this is largely due to the improvements in the energy efficiency of the HEO.

3.2. *Life cycle costs*

The life cycle costs, shown in Fig. 6, range from €320 to €479 over the lifetime of the conventional oven (assuming constant prices over time). The main cost driver is the energy use, contributing 53%–79% of the total LCC, depending on the cleaning option. If used, pyrolytic cleaning accounts for 31%–45% of the total costs because of the electricity used during the process (see Table 2). The costs of the raw materials contribute the remaining 1.5%–2% while the contribution of manufacturing is negligible. For the conventional oven using oven cleaner, the use stage is responsible for 79% of the total costs, while the oven cleaner and raw materials account for 18% and 2%, respectively.

The LCC of HEO1 range from €247 for HEO1 to €194 for HEO3. The cost of energy in the use stage is the dominant contributor, accounting for 94% of the total LCC so that the cost to the consumer is equivalent to €232 for HEO1, €217 for HEO2 and €180 for HEO3 over the lifetime of 19 years. For the best option, HEO3, this represents a saving of 41%–61% over the lifetime, depending on the cleaning option assumed for the conventional oven. Even for the worst HEO option (HEO1), 25%–50% of the lifetime costs would still be saved by the consumer. Like the environmental impacts, the end-of-life waste disposal costs are negligible, accounting for less than 1% of the total LCC for all the options over the lifetime of 19 years.

3.3. *Sensitivity analysis*

This section explores the effect of three key variables on the impacts and costs: the lifetime of ovens, electricity consumption by the oven over its lifetime and household electricity prices. The trends in the results for the GWP and the other impacts are similar so that only the GWP is considered here, alongside the LCC.

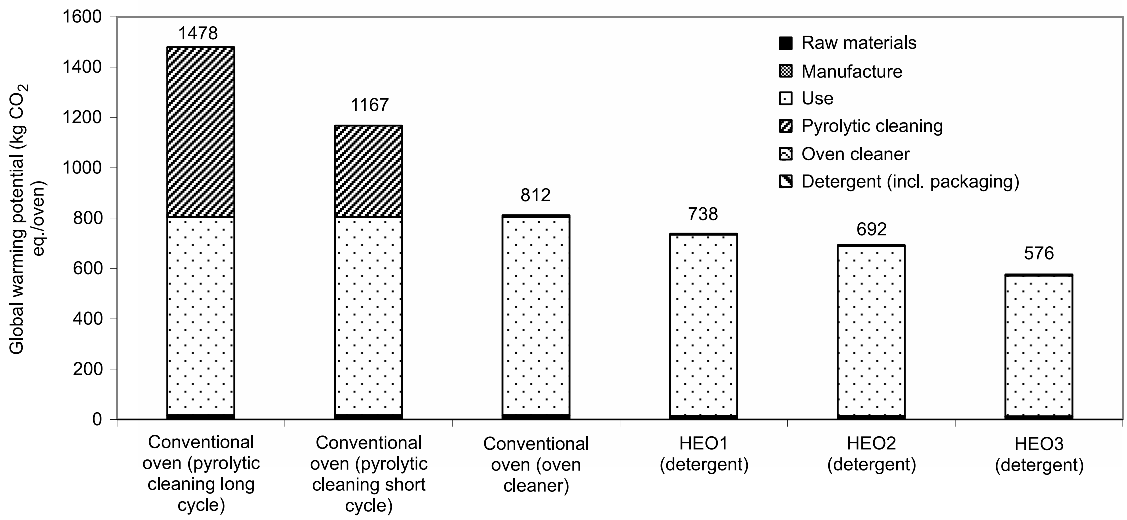


Fig. 4 – Global warming potential of the conventional and highly-efficient ovens over the lifetime of 19 years. (Raw materials include energy for enamelling. Manufacture refers to the manufacture of the oven cavity. Use includes end-of-life waste disposal. HEO1: 0.63 kWh/cycle; HEO2: 0.59 kWh/cycle; HEO3: 0.49 kWh/cycle.)

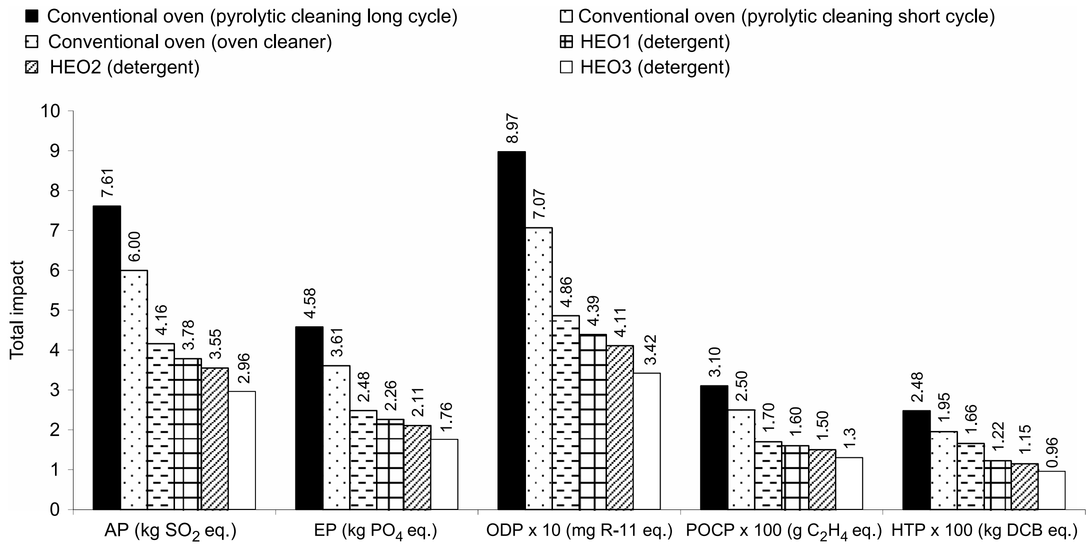


Fig. 5 – Environmental impacts (other than the GWP) of the conventional and highly-efficient ovens over the lifetime of 19 years. (AP: acidification potential, EP: eutrophication potential, ODP: ozone layer depletion potential, POCP: photochemical oxidants creation potential (photochemical smog), HTP: human toxicity potential, DCB: dichlorobenzene. Some impacts have been scaled to fit. The scaled values should be multiplied by the factor shown in brackets against the relevant impact to obtain the original value.)

3.3.1. *Oven lifetime*

In addition to the originally assumed 19-year lifetime of the ovens, a shorter lifetime of 10 years is considered here. The results are compared in Fig. 7 for both the GWP and LCC. As can be inferred from the figure, the GWP savings of HEO relative to the conventional oven are greater over 10 than over 19 years. For example, the saving in the impact for HEO3 compared to the conventional model cleaned using the long pyrolytic cycle is 72% over 10 years; the corresponding saving over 19 years is 61%. This is because of the high contribution of energy for cleaning the oven, which is proportionally lower over 10 than 19 years. This benefit disappears if an oven cleaner is used instead of the pyrolytic cleaning so that the relative savings in the GWP over 10 and 19 years are the same (e.g. 29% for HEO3).

On the other hand, there is little change in the relative difference between the LCC for the 10 and 19-year lifetimes, exhibiting the opposite trend to the GWP: the cost savings are greater over the longer lifetimes, but only by 1%–2% across the above options.

As can also be seen in Fig. 7, as expected, the total GWP and LCC are lower over the shorter lifetime as less energy is consumed. However, this does not take into account that the consumer would have to buy a new oven after 10 years so that the total impacts and costs would be much higher. This aspect is beyond the scope of the study since only the cavity is considered rather than the whole oven.

3.3.2. *Electricity consumption*

To examine the impact of electricity consumption in the use stage, different scenarios for electricity consumption are considered and these results are shown in Figs. 8 and 9 for the GWP and LCC, respectively. The savings in the GWP and costs are expressed as a function of 'delta energy' which represents

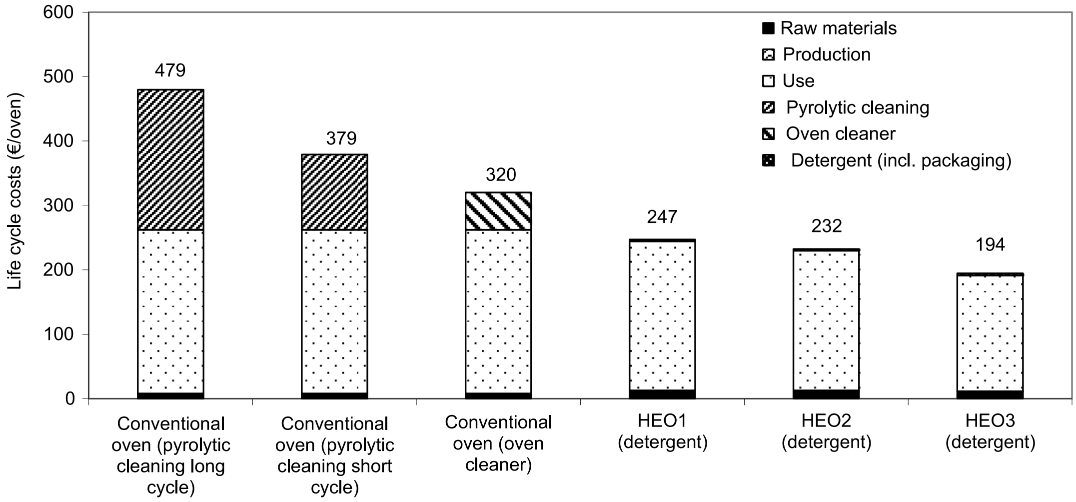


Fig. 6 – Life cycle costs of the conventional and highly-efficient ovens over the lifetime of 19 years. (Use includes end-of-life waste disposal. Constant costs are assumed over the lifetime of the ovens.)

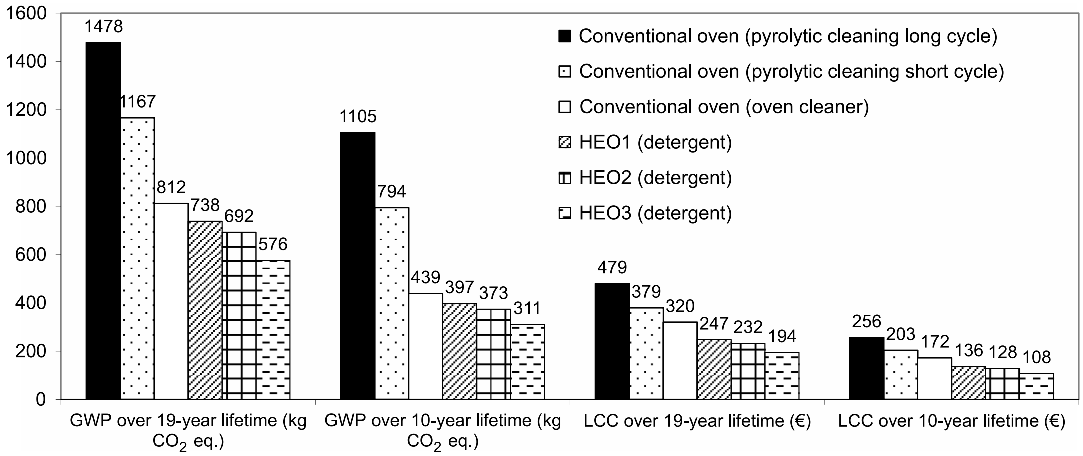


Fig. 7 – Influence of the oven lifetime on the global warming potential and life cycle costs of the conventional and highly-efficient ovens. (Constant costs are assumed over the lifetime of the ovens.)

the difference in electricity consumption per cycle between the conventional oven and HEO. These findings have been used to guide improvements in the design of HEO during the development process.

As indicated in the figures, the GWP and cost savings increase linearly with the increase in 'delta energy' between the two types of oven. For example, for every 0.1 kWh increase in energy efficiency of HEO, 115 kg CO_2 eq. and €37 are saved over the oven's lifetime of 19 years. While per single oven this may not appear to be significant, at the European level, the savings are much more substantial; this is discussed further in Section 3.4, but prior to, we examine the effect on the LCC of rising the household electricity prices over time.

3.3.3. *Household electricity prices*

The impact of electricity prices on the LCC is compared to the base case for the conventional oven and the HEO for both the 19 and 10-year lifetimes. A year-on-year annual increase of 1.4% in household electricity prices is assumed (European Commission, 2009). As the focus is on energy prices, the costs of cleaning are excluded for both types of oven. The results in Fig. 10 indicate that increasing household electricity prices would lead to 12% higher costs over the lifetime of 19 years and a 6% higher costs over 10 years, for both the conventional oven and HEO. Therefore, while the effect of rising the costs of electricity are significant for the consumer, the relative difference between the conventional oven and HEO remains the same.

3.4. *Potential impacts at the EU28 level*

This section considers the climate change and cost impacts of a potential replacement of conventional ovens by the HEO in Europe, considering 28 EU countries. The analysis is based on the number of households in EU28, estimated at 213.8 million in 2013 (Eurostat, 2014). It is assumed that 61% of EU28 households (130.4 million) use electric ovens (Bertoldi et al., 2001). The assumptions for the energy consumption by the conventional ovens and HEO are the same as previously, with 110 use cycles and 10 cleaning cycles annually (see Table 2). The results are presented in Figs. 11 and 12.

Assuming the worst case whereby all households with conventional ovens use long pyrolytic cleaning cycles, the total annual GWP is estimated at 10.1 Mt of CO_2 eq. and the LCC at €3.29 bn (see Fig. 11). If HEO1 were to replace all of the ovens, 50% or 5.08 Mt of CO_2 eq. would be saved in total and the LCC would be reduced by 61% or €1.6 bn. Most of the latter would be direct consumer savings because of the reduced energy consumption. The corresponding savings for the best HEO option (HEO3) are higher still, estimated at 6.23 Mt CO_2 eq. and €1.96 bn, respectively. If, on the other hand, it is

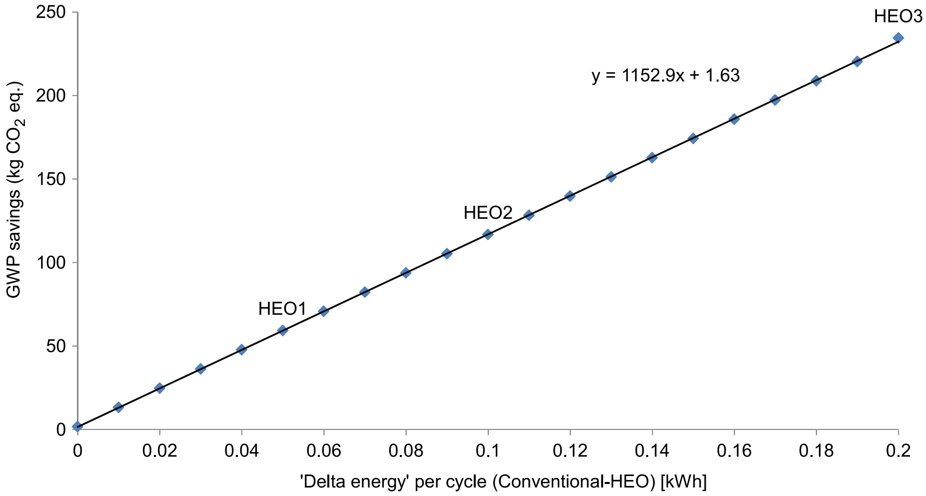


Fig. 8 – GWP savings over the lifetime of 19 years expressed as a function of a difference in electricity consumption in the use stage between the conventional oven and HEO.

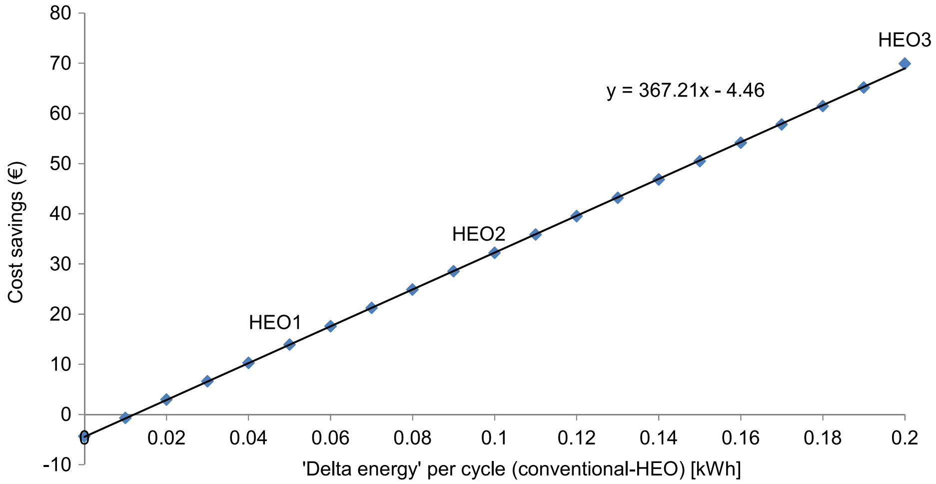


Fig. 9 – Cost savings over the lifetime of 19 years expressed as a function of a difference in electricity consumption in the use stage between the conventional oven and HEO.

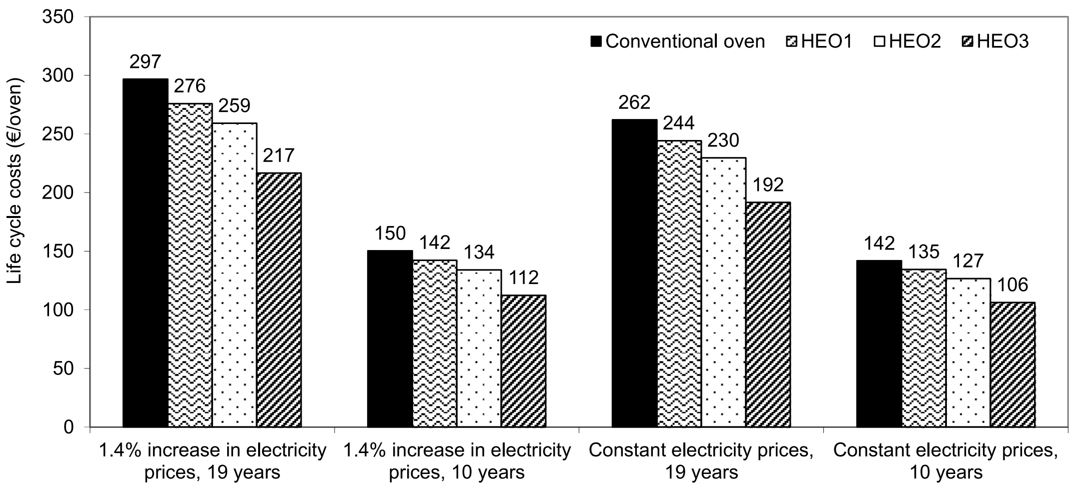


Fig. 10 – The effect on the life cycle costs of rising electricity prices over the lifetimes of the conventional ovens and HEO. (Year-on-year annual increase in consumer electricity prices of 1.4% is assumed. Oven cleaning is excluded.)

assumed that all consumers used only detergent for cleaning the conventional ovens, the GWP savings range from 9%–30% and LCC from 23%–39% for the HEO1 and HEO3, respectively. Assuming an uptake rate of 5% per annum starting in 2015, it would take 20 years, to 2034, to achieve these benefits (see Fig. 12(a) and (b)). At a 10% penetration of HEO per year, these savings would be realised by 2025 while at a slower uptake rate of, for example 3%, it would take up to 2046 before all the conventional ovens are replaced by HEO. However, it should be noted that these results would vary among the individual

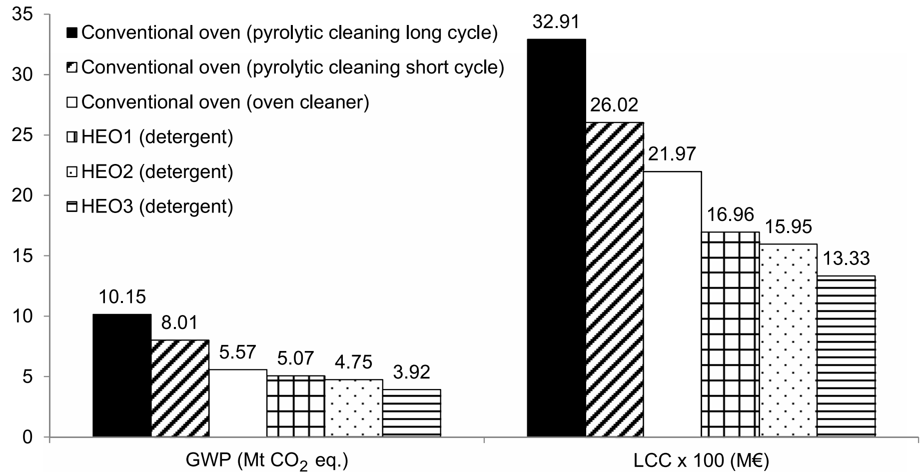
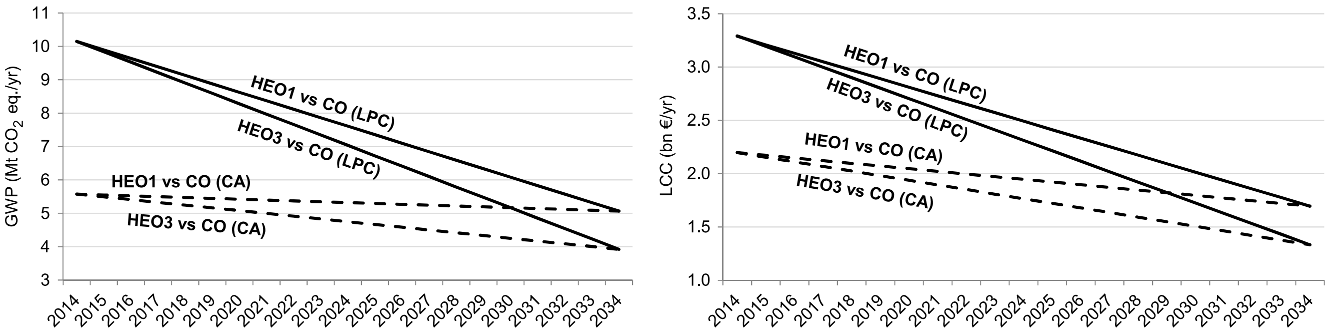


Fig. 11 – Annual global warming potential and life cycle costs of conventional and highly-efficient ovens in the EU28. (Electricity consumption per cycle: conventional oven 0.69 kWh; HEO1 0.63 kWh; HEO2 0.59 kWh; HEO3 0.49 kWh. 110 use cycles annually. Pyrolytic cleaning: 3.5 kWh per cycle (short cycle) and 6.5 kWh per cycle (long cycle), assuming 10 cleaning cycles annually. The LCC values have been scaled to fit and should be multiplied by 100 to obtain the original values.)



(a) Global warming potential. **(b) Life cycle costs.**

Fig. 12 – Reduction trends for the GWP and LCC if HEO replaced conventional ovens in the EU28 at a 5% annual uptake rate. (CO (LPC): conventional ovens with long pyrolytic cleaning; CO (CA): conventional oven using cleaning agent. Electricity consumption per cycle: conventional oven 0.69 kWh, HEO1 0.63 kWh and HEO3 0.49 kWh. Pyrolytic cleaning (long cycle): 6.5 kWh per cycle, 10 cleaning cycles annually.)

EU28 member states because of different electricity mixes, number of households that use electric ovens and consumer behaviour.

The results of the analysis demonstrate that replacement of conventional domestic electric ovens by highly-efficient models would be beneficial from both the environmental and economic perspectives. However, to promote the uptake of HEO, the use of fiscal instruments may have to be considered. A number of options have been suggested by the European Committee of Domestic Equipment Manufacturers (CECED) as effective for promoting the uptake of energy efficient household appliances including tax credits granted directly to consumers, consumer purchase rebate or cash-back schemes and tax credits to consumers coupled with tax credits to manufacturers (CECED, 2007; GAP, 2012). However, any such initiatives would have associated cost implications which should be considered carefully to avoid unintended consequences, often associated with fiscal instruments. Financial incentives should also be accompanied by a wide-ranging awareness raising among consumers as most are not aware that cooking, and particularly ovens, are significant energy consumers (Hoolohan and McLachlan, 2015) and that they could save money by switching to more efficient appliances. An example of a successful awareness raising campaign in the EU, accompanied by financial incentives as well as legislation, are light bulbs. To phase out energy-inefficient types, a concerted campaign involving awareness raising and free low-energy bulbs was rolled out across Europe, leading to a much faster uptake than would have happened otherwise. In addition, some types have been banned, notably 100 W incandescent bulbs. As it is going to be much more difficult to convince the consumer to replace household appliances than bulbs, similar 'choice editing' may be needed to help phase out energy-inefficient models more rapidly.

4. Conclusions

This study has considered life cycle environmental and economic impacts of conventional and novel highly-efficient ovens. The GWP of the former ranges from 812–1478 kg CO_2 eq. and of the latter between 576–738 kg CO_2 eq. over the lifetime of 19 years. Therefore, HEO ovens have a potential to save up to 30% of energy and between 9% and 61% of the GWP, depending on the assumptions for the cleaning options for the conventional oven as well as on the amount of electricity used per cycle by HEO. Most of the GWP for both oven types is generated during the use stage, with the electricity contributing 53%–97% to the total. The raw materials contribute around 1%–2%, while the manufacture of the oven cavity accounts for less than 1% of the total impact. The other environmental impacts are reduced by 24%–62%.

The LCC of HEO are also lower than for the conventional oven, ranging between €194–247 per oven over its lifetime, compared to €320–479 for the conventional oven. In the best case (HEO3), the consumer could save 41%–61% over the lifetime of the oven, depending on the cleaning option assumed for the conventional oven. Even for the worst HEO option (HEO1), 25%–50% of the lifetime costs would still be saved by the consumer.

At the EU28 level, the results suggest that replacement of conventional domestic electric ovens by highly-efficient models would lead to significant environmental and cost savings ranging from 0.5–5.2 Mt CO_2 eq./yr and €0.5–1.96 bn/yr, respectively. Most of the latter would be direct consumer savings because of lower energy consumption. Assuming an uptake rate of 5% per annum, it would take 20 years to achieve these benefits at the EU28 level. At 10% annual uptake per year, these savings would be realised in half the time while at 3% it would take 33 years. Therefore, policy makers should consider measures to encourage the uptake of energy efficient ovens, including financial incentives and 'choice editing' through legislation.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.spc.2015.12.004.

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